Response to Susan Kulawik's referee comment on "Does GOSAT capture the true seasonal cycle of XCO2?"

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We thank the referee Susan Kulawik for her thorough and positive review of our paper and for her remarks that helped us improve the paper. In this letter, we respond to her comments (the original comments are shown here with *italic, blue text*) and indicate the changes made in the manuscript in reaction to her comments.

This paper looks at the seasonal cycle amplitude from ACOS-GOSAT, 4 other GOSAT algorithms (RemoTeC, NIES, UoL, NIES-PPDF), and 3 models (CT2013B, UoE, Macc13.1) vs TCCON at 12 northern hemisphere TCCON sites and in latitude and longitudinal bins in the Northern Hemisphere. The seasonal cycle peak and minimum times, and secular increase are also investigated. The focus is on ACOS-GOSAT, and changes are explored for comparisons with ACOS-GOSAT such as different co-location schemes, aerosol treatment, and bias correction changes. The 5 other models and GOSAT algorithms are shown for comparison. The analysis finds a too-shallow seasonal cycle for ACOS-GOSAT for European sites, but not in other GOSAT algorithms, and finds that when 2 components of the ACOS bias correction algorithm are removed, the seasonal cycle agreement improves but at the cost of larger single target errors. Other findings include that model-to-model variability in the seasonal cycle amplitude can be up to 2-3 ppm in regions poorly constrained by in situ data, e.g. (45N-50N,120- 180E) or (0-25N). At the TCCON sites, the ACOS-GOSAT seasonal cycle error compared with TCCON is on the order of 1.0 ppm.

The paper is logically presented and well written; the content and presentation and quality are appropriate to ACP. The attributes that are studied are important for accurate flux estimates using GOSAT data, as errors will lead to systemic errors in flux estimates. Additionally, the comparison of the different GOSAT algorithms is very interesting as well as the large model-to-model variability in different parts of the world.

General comments:

The amplitude of the GOSAT fit should be viewed with caution above 60N where the gaps in the seasonal cycle could cause significant fit errors. When comparing to models, the same data gaps should be applied to both the models and the GOSAT and TCCON data.

The models have been resampled at exact GOSAT soundings in latitude, longitude and time, and therefore take into account the gaps in the satellite data.

The amplitude and phase of the fit may be partially prescribed by the fit function that is used, e.g. the fit of data far from the peak could affect the peak location and amplitude, so it is important to assess the fit minus data residuals for signal. The *seasonal cycle peak and minimum might be more accurately calculated with a local smoothing function rather than a prescribed globally fit function. For this paper, plots and assessment of fit minus data residual signals, especially near the peak and minimum, and discussion of the above should be included if there are residual signals.*

Based on this comment, we made the plots of the residuals for each TCCON site, and found that there was no systematic signal left in the residuals. We identified few non-systematic, small-scale features at a few sites (for example at Bialystok) but these were something that would be extremely difficult to fit out anyway. We added the following sentence to Sect. 4.3 to briefly summarize these studies: "To ensure that the amplitude and phase of the seasonal cycle were not determined largely by the fit function, we assessed the fit-minus-data residuals for both TCCON and ACOS, and could not identify any systematic signatures in the residuals."

"As model-to-model differences in XCO2 can be several ppm at regions poorly sampled by in-situ measurements, GOSAT observations that measure seasonal cycle amplitude to within 1.0 ppm, based on this study, could potentially be used directly (without elaborate inversions) to evaluate model differences at these regions."

The statement that GOSAT observations that measure seasonal cycle amplitude to within 1.0 ppm globally should be qualified. The satellite retrievals depend on a priori knowledge of the interferent species, like aerosols, temperature, and water, which will be better constrained in Europe and North America where most TCCON stations are. These errors may be larger in other parts of the world. The statement should be modified to something like "whereas the ACOS-GOSAT seasonal cycle error is on the order of 1.0 ppm near TCCON stations and likely to be of this size in other parts of the world, though may be influenced by the a priori accuracy of jointly retrieved parameters."

This should be updated in the text and conclusions.

Based on this reasonable comment, we modified the text in the conclusions as follows: "Based on our study, the GOSAT/ACOS seasonal cycle error is of the order of 1.0 ppm near TCCON stations and likely to be of this size in other parts of the world, though may be influenced by the a priori accuracy of jointly retrieved parameters, such as those related to aerosols. As model-to-model differences in the XCO_2 seasonal cycle amplitude can be several ppm at regions poorly sampled by in-situ measurements, GOSAT observations could potentially be used directly (without elaborate inversions) to evaluate model differences at these regions. This idea is explored in more detail in a work under preparation (Lindqvist et al., 2015)."

Specific Comments:

Page 4 line 100: "likely to be affected by any seasonal biases present in the GOSAT/ACOS retrievals that are due to the ACOS system itself." change to "likely to be affected by any seasonal biases present in the GOSAT/ACOS retrievals that are due to the ACOS system or ACOS a priori inputs."

Corrected as suggested.

Page 5, line 130 "Their validated and calibrated higher precision and accuracy compared to satellite observations, coupled with the fact that they measure the same quantity in essentially the same way as the satellites" change to " coupled with the fact that they measure the same quantity in essentially the same way as the satellites, though looking directly at the sun rather than sunlight reflected off the earth, so are not affected by surface albedo, "

Corrected as suggested.

Page 5, line 145. The southern hemisphere amplitude is small, however it is has large flux uncertainties and less in situ data, so that satellites could add significant guidance to models. I would not discount it but rather state why your analysis is not appropriate for it or that you choose to focus on the northern hemisphere.

We added the following sentence to the manuscript Sect. 3.1: "We therefore chose to focus on the Northern Hemisphere, which has both a larger seasonal cycle amplitude, and a larger quantity of TCCON stations against which to compare."

Page 5, line 190. It doesn't seem like TCCON should be hyphenated at a line breake.g. TC-CON.

Corrected throughout the LaTeX document.

Page 7, line 219, "Finally, we calculated daily averages of both GOSAT/ACOS and TCCON retrievals." What is the local time of TCCON that is averaged? Is it the time averaged for TCCON around the time of the GOSAT observations? Please state.

We modified the sentence to clarify this: "Finally, we calculated daily averages of co-located GOSAT/ACOS and TCCON retrievals."

Page 8, line 235. The "daily error" for GOSAT/ACOS and TCCON are of interest, so state what they are.

This confusing term has been replaced with "σ of each daily-averaged XCO_2".

Page 8, line 235. The fit chosen may also not be the correct seasonal fit, so it is important to note whether the TCCON error (in particular since TCCON errors are smaller) is randomly distributed about the fit. This can be shown with a difference plot, e.g. with green dots around the dashed lines in figure 4, or in a separate figure, in particular for a case where there are larger differences in the maximum location.

According to our additional studies made during the revision, the fit - TCCON residuals are small and randomly distributed, with no systematic signal.

Page 8, Equation 1. cos-1() has a domain issue in that cos-1(x) will range from 0 to pi, rather than -pi to pi. I can't quite wrap my mind around what sin(cos-1(acos(wt))) does. Could you give the fit values for a0-a5 for at least one example, *e.g. Park Falls. I assume that the cos-1() term is to give a time-dependent phase. Is this a standard equation for fitting a seasonal cycle? Is there a reference for this fit? It doesn't matter if there is a reference if it does a good job; the quality of the fit should be assessed by looking at residuals of fit-data (see general comments).*

Unfortunately we do not have a special reference for the fit; the function is one of many ways of creating a so-called skewed sine wave, and to our knowledge has not been used in a seasonal cycle context before. This domain issue pointed out by the referee is true for Eq. (1) and in practice means that, for certain parameter combinations, the fitted function has unphysical discontinuities and regions where it does not exist. However, it turned out that such parameter combinations (even though they were allowed by the nonlinear fitting procedure) never resulted in the lowest chi square values, and were excluded on that basis. As an example, we added the fit parameter values to Table 2 for the TCCON and ACOS fits at Park Falls.

Page 9, Line 286, "The satellite observes the maximum later than the TCCON at the European sites, but obtains good agreement elsewhere. At the European sites, the difference extends up to 2–3 weeks, and is likely connected with the biased amplitude inferred by ACOS discussed below." Fitting can create phase differences if the fitting function does not match the data shape (see general comments). Can a plot be shown of the GOSAT/ACOS and TCCON data for a station where there is a phase difference between TCCON and GOSAT so that the reader can see that the data supports the fit shape? Kulawik et al., 2015 used cross-correlation to determine phase shift and found a much smaller phase difference in Europe, which seems in disagreement of your findings.

This is an interesting observation and definitely worth a comment in the text. We decided not to add another figure, however, but instead explain how we derived error statistics for the fitted maximum and minimum, because these statistics reflect the statistical uncertainty in the fit. We expanded the text as follows: "However, regarding the difference in the dates of the maximum, Kulawik et al. (2015) found a much smaller phase difference in Europe by using cross-correlation to determine the phase shift. Because our results were based on the fitted seasonal cycles instead of the actual data, we evaluated the statistical errors of the dates of the maximum and minimum XCO_2 with a Monte Carlo approach, using the error covariance matrices associated with the fitted function parameters. The deviations from the fit maximum and minimum followed a normal distribution with an average σ of 3.5 days for the TCCON maximum date, and 6.1 days for ACOS maximum date, reflecting a notable uncertainty in the fitted phase. The corresponding average σ for the date of the minimum were 2.2 days (TCCON) and 3.6 days (ACOS)."

Page 12, line 390, " These results can be interpreted to support the ensemble median algorithm EMMA introduced by Reuter et al. (2013), which combines all individual retrievals into one data set that globally has the best agreement with TCCON." It would be useful to add EMMA to Figure 6.

We repeated the analysis for EMMA and it turned out that EMMA was neither the best nor the worst when compared to TCCON by the measures that we use in Fig.

6. However, we would prefer not to replace Fig. 6 with a version where EMMA is included because the figure is already quite busy with symbols and because EMMA did not outperform the other algorithms in any of the panels. We updated the sentence in the text accordingly: “Since none of the retrieval algorithms clearly outperformed the others at every TCCON site, we repeated the analysis for the ensemble median algorithm EMMA (Reuter et al., 2013), which combines all individual retrievals into one data set of median XCO_2 values. Even though EMMA had the smallest RMS error at four TCCON sites overall, it did not perform systematically better or worse than the individual retrieval algorithms in capturing the seasonal cycle of XCO_2.”

Page 12, line 405, " The seasonal cycle was fitted on the daily averages of GOSAT/ACOS XCO2 and the resampled models." The models were presumably sampled in the daytime? It is important to match the approximate GOSAT overpass time. Also, see general comments, gaps in the GOSAT data can result in differences from a complete seasonal cycle.

We agree that matching the GOSAT overpass time is important, and therefore (as explained in Sect. 3.2) all modeled XCO2 data were resampled at exact GOSAT observations in latitude, longitude and time, so the model seasonal cycles include the same gaps as the satellite data does.

Page 13, line 427, "From 60_ to 70_, ACOS has a higher seasonal cycle amplitude than most models." North of 60N the gaps in GOSAT seasonal data are such that the peak fit of the seasonal cycle is likely outside of the seasonal span of GOSAT data, see general comments. To compare to model fits, both models and data should have the same data gaps.

As already mentioned in the general comments, the models and the satellite data both have the same data gaps because we resample the model values at the GOSAT soundings. The winter gap north of 60 degrees latitude is indeed wide, but it appears that we observe the maximum or at least the time very close to it (at least in most years) because the XCO2 values increase during the first (roughly) 10-20 days before they start to decrease.

Page 13, line 440, that the averaging kernel correction results in a modest systematic effect on the seasonal cycle amplitude is an important finding which should be mentioned in the conclusions. A seasonally dependent 0.2 ppm error could have a significant impact on flux estimates.

We added this finding in the Conclusions as follows: “We also noticed that the averaging kernel correction can systematically decrease the seasonal cycle amplitude by up to 0.2 ppm, and thus should not be neglected.”

Page 15, line 508. Accuracy of GOSAT/ACOS results has dependence on prior information of the interferents and some caution is a warranted regarding the accuracy far from TCCON sites.

As pointed out in our replies to the General comments, we have modified this sentence to take into account the fair and valid concerns of the referee. It is true that without further validation studies we simply cannot know how accurate the GOSAT soundings are far from the TCCON sites, although we do not expect the accuracy to deteriorate notably, because the TCCON sites used in validation already cover a variety of different atmospheric and geographic conditions.

Figure 2. The tan background makes the colors hard to see.

The figure colors have been changed (currently this is Figure 2b). We also added in the US state borders and the provincial borders for Canada.

Figure 5 label: Refer to Panel (a) and Panel (b) rather than Panel a and Panel b.

Corrected as suggested.